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FROST HEAVE MONITORING RESULTS AT SELECTED TRANSFORMER STATIONS - WINTER 1987/88

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Several transformer stations have reported heaving of light equipment foundations. To assess remedial designs, four types of test footings were installed and monitored at Port Hope TS, Ottawa-Hawthorne TS and Pinard TS. Results of a second year of field monitoring indicate that the winter of 1987-88 was warmer than normal in southern Ontario, leading to less frost penetration and ground heave. In northern regions, temperatures were generally normal, however, increased snow cover protected the soil from extensive frost penetration. This phenomena is examined by application of the Bergreen equation which estimates frost depth. It is recommended that field monitoring be discontinued for the present and that emphasis be placed on controlled testing of footing heave in the laboratory.

1.0 INTRODUCTION

Frost heaving of light equipment foundations has been reported at several transformer stations across Ontario. As part of a program to evaluate remedial design options a field monitoring study of trial remedial foundations was initiated in the fall of 1986.

The field program involved installing four types of test footings (shaft/sleeve, augered, insulated and screw-in at three transformer stations: Pinard TS north of Timmins, Ottawa-Hawthorne TS and Port Hope TS). Several sets of frost depth and frost heave gauges were installed in the vicinity of the footings to monitor ground response to freezing temperatures. Gauge readings and footing surveys were made at regular intervals throughout the winter months.

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Details of the footing and instrumentation layouts, and results of the 1986/87 field and laboratory testing programs are reported in Research Report No 87-253-K/1/. One of the recommendations of the above report was that the field monitoring program be continued during the following winter, mainly because the winter of 1986-87 had been milder than normal, resulting in unrepresentative frost depth and frost heave measurements.

This report presents the results of the field monitoring program at the three transformer stations during the winter of 1987/88.

2.0 FIELD MONITORING RESULTS

The monitoring data gathered over the winter of 1987/88 for Port Hope TS, Ottawa-Hawthorne TS and Pinard TS are presented in Tables I, II and III respectively. The results are tabulated as changes in footing elevation, changes in frost heave gauge position, absolute frost depths and thermocouple readings where applicable.

Air temperature data are also available from four Environment Canada weather stations at Port Hope, Ottawa CDA, Island Falls and Smoky Falls. The latter two stations are located southeast and northwest respectively of Pinard TS. The temperature data are plotted in Figures 1 to 4 as monthly freezing degree-days (Celsius) from October to April for all four weather stations. Along with the monthly freezing degree-days for 1987 and 1988, the mean monthly values and plus or minus one standard deviation values are plotted for the period 1970/88.

2.1 Port Hope TS

In the fall of 1987, major disturbances occurred to the test footings and instrumentation area due to local construction activities. Footing #2 (augered), as shown in Figure 5, was completely removed, granular cover material on top of the insulation of Footing #3 was disturbed and frost heave gauges A, B and C were damaged but remained in usable condition.

Figure 1 is a plot of monthly freezing degree-day averages for Port Hope. The mean and standard deviations are also plotted for the 1970-88 period. The months of December and January 1988 were much warmer than normal while February and March were normally cold.

Frost depths during February and March ranged from approximately 42 to 48 cm in the areas between the footings and from 53 to 56 cm away from the footings. Based on Brown's 1964 relationship/2/ and an approximate freezing index of 450 degree days (^{0}C) for 1987-88, the frost depth can be estimated at 1.1 metres which is twice the actual recorded depth. Frost depths between the test footings in 1986-87 were less than half those recorded during this study/1/. Although the freezing degree-days for 1986-87 were less than for 1987-88, the substantial disturbances made in the area of the test footings may have contributed to the greater frost penetration.

Of the frost heave gauges remaining (B, C and D), both B and C recorded slightly more heave in 1987-88 than in 1986-87. In contrast, the test footings remaining (1, 3 and 4) showed less heave in 1987-88 than 1986-87.

These opposing results tend to question the reliability of these types of field measurements. The thermocouple readings taken from underneath the insulated footing, indicate that thermal gradients were greater in January and February of 1988 than 1987 and absolute temperatures were also lower.

2.2 Ottawa-Hawthorne TS

The freezing degree-days for the Ottawa area are plotted in Figure 2. The winter of 1987-88 was similar to 1986-87, except for the month of March which proved colder during the second year of this study. The total of freezing degree-days for 1987 was 815, and for 1988 was 832. More snow was also recorded in 1987, reaching a maximum of 32 cm, compared to 1988 when the maximum was only 13 cm.

The maximum frost depth recorded was 15.2 cm at gauge A. This value is substantially less than expected, based on the recorded freezing degree-days, and is also less than that recorded in March of 1987 even though winter temperatures were approximately the same for both years.

A maximum of 1.9 cm of heave was recorded at frost heave gauge D, located away from the test footings. No heave was recorded at gauges A, B and C, which is similar to the results of 1987 when none of the gauges responded.

A maximum heave of 0.6 cm was recorded for test footings #3 and #4 (insulated and Chance footings) during February. Although the Chance and shaft/sleeve footings behaved similarly during both winters, the insulated and augered footings apparently heaved much less in 1988 than 1987, based on surveying results tabulated in Table II.

2.3 Pinard TS

The freezing degree-days for Pinard TS are represented by results from the Island Falls and Smoky Falls weather stations. Figures 3 and 4 indicate that the winter of 1988 was substantially colder than the winter of 1987. Total freezing degree-days (^{o}C) at Island Falls were 2020 for 1988 and 1560 in 1987. However, a maximum snow cover of 88 cm was recorded in February of 1988 which contrasts to the maximum value of 44 cm recorded in the same month in 1987.

The effect of the added snow cover is reflected in the lower frost depths recorded for 1988 and tabulated in Table III. The maximum value recorded was 9.5 cm. The same type of results were recorded for the frost heave gauges and the test footings, where very little movement was recorded during the winter of 1988.

The thermocouple readings available for February and March/88 indicate that the magnitudes of ground temperatures under the insulated footing were similar to those recorded in 1987. The thicker snow cover in 1988 helped maintain temperatures above freezing, even though the winter temperatures were much lower than in 1987. Because a thermocouple tree was not installed at any other location, it remains unclear why less frost penetration was recorded, even though similar ground temperatures were observed for both 1987 and 1988.

2.4 Conclusions

In general, the winter temperatures in southern Ontario were very similar between 1987 and 1988. The results of this past year's monitoring are therefore similar to those reported in 1987, which means to say, largely inconclusive. Although more frost penetration and ground heave were recorded at the Port Hope site, the associated test footings heaved less. These results may have been influenced by the large local disturbances caused by construction at the transmission station. Less frost penetration and footing heave were recorded at Ottawa-Hawthorne in 1988, even though winter temperatures were similar to 1987 and there was less snowfall.

The winter of 1988 in northern Ontario was much colder than in 1987. However, a thicker snow cover provided extra insulation, resulting in less frost penetration, less ground heave and less footing heave than recorded in 1987.

The objective of determining which footing type is less susceptible to frost heave has not been met to date. This result is largely due to inconsistent and complex weather conditions and to difficulties associated with collecting field data from remote sites.

3.0 EMPIRICAL FROST DEPTH PREDICTIONS

The importance of snow cover, acting as an insulating blanket against frost penetration, may be assessed through the application of simplified theoretical equations. One such equation is the modified Bergreen equation which is applicable to semi-infinite and homogeneous ground conditions/3/. By assuming that the temperature gradient in a soil is linear, the frost depth may be calculated by the following equation:

$$x = \lambda \sqrt{\frac{48\ kfN}{L}} \qquad \text{.....1}$$

where x = depth of frost penetration (cm)
k = thermal conductivity of soil (cal/cm/hr/^{o}C)
f = conversion factor for air-index to ground surface index (dimensionless)
N = air freezing index (degree-days)
λ = coefficient taking into account the effect of temperature change in the soil mass
L = latent heat of fusion for converting soil water into ice (cal/cm^{3})

A step-by-step procedure for solving the above equation, as well as equations applicable to multi-layered systems, is described by Sumar and Lee/4/. Their report includes several charts and nomographs for obtaining volumetric latent heat, heat capacity and thermal conductivity of soils based on densities and moisture contents.

A simple application of the Bergreen equation is to calculate the frost depth at Pinard TS during 1988, assuming no snow cover. The charts and nomographs

in Sumar and Lee/4/ are in imperial units and therefore unit conversion will only be applied to the results.

Assuming a bulk density of 119 pcf and a moisture content of 15%, the nomographs provide the following parameters: Heat capacity (C) = 34 Btu/cu ft^{o}F; Volumetric latent heat (L) = 2500 Btu/cu ft; thermal conductivity (K) = 1.65 Btu/(h-ft-^{o}F). The mean annual temperature at Abitibi Canyon is 31.7 ^{o}F/5/, therefore V_o = -0.3^{o}F. The following parameters are also required for the calculation:

f = 0.7 (sand and gravel surface)
N = 3636 degree-days ^{o}F for Island Falls
t = 150 days (number of days without thawing)
V_s = (f x N)/t = 16.95^{o}F
μ = fusion parameter = V_s x C/L = 0.23
α = thermal ratio = V_o/V_s = 0.0
λ = 0.96

Substituting the above parameters into equation 1 gives

$$x = 0.96 \left(\frac{48 \times 0.7 \times 1.65 \times 3636}{2500}\right)^{1/2}$$

= 8.62 feet
= 2.63 metres

This frost depth value agrees very well with the one estimated from Brown's 1964 relationship, but does not agree with frost depth measured in the field. Even though use of the Bergreen equation does not appear to agree with field results, the equation may be used to study relative changes in frost penetration with respect to snow cover thickness.

The method for determining frost penetration in multi-layered soils, or soils with an insulating cover, is described by Sumar and Lee/4/. The calculations are similar to the one presented above, except that the surface freezing index required for frost to penetrate each layer is calculated. The indices are successively summed and compared to the available freezing index for the site in question, until an agreement is reached. In the case of an insulating layer overlying only one soil unit, the equation for determining frost depth is given by:

$$x^2 + (2K_1R_{in})x - (48\lambda_1{}^2 N K_1)/L_1 = 0 \quad \text{.....(2)}$$

where L_1, K_1 and λ_1 are parameters associated with the first soil layer
R_{in} = thermal resistance of insulating layer
= d_{in}/K_{in}
d_{in} = insulation thickness (ie snow cover)
K_{in} = thermal conductivity of insulation

The parameters used in the analysis were similar to the ones listed in the previous example, with the following exceptions:

K_{in} (snow) = 0.225 Btu/(hr ft^{o}F)/6/
f = 1.0 (snow cover)/4/

The solution of the above quadratic equation gives the frost depth, x. Since Equation 2 does not contain the f-factor for reducing the air-freezing index to the surface-freezing index, there will be some disagreement with Equation 1 in the case when insulating thickness is zero.

The results of this analysis are shown in Figure 6, which is a plot of snow cover thickness versus depth of frost penetration. Two curves are plotted representing different freezing degree-days for two years, 1987 and 1988. The insulating capacity of a thin layer of snow is dramatically illustrated by this plot. For the winter of 1988, a 30 cm thick layer of snow cover had the capability of reducing frost penetration from 3.1 m to 1.5 m. Increases in the amount of snow cover reduce frost penetration even more, but only at an exponentially decreasing rate. These calculations demonstrate the importance of an early snow cover to prevent frost penetration later in the winter. This also may help explain the small frost depth recorded at Pinard TS during the winter of 1987-88, when approximately 50 cm of snow was on the ground by December.

A theoretical frost depth of 95 cm was calculated for the Port Hope area, using a freezing index of 380 degree-days Celsius and no insulating cover. The freezing index used represents the winter of 1987. A similar frost depth could have been experienced at Pinard TS if the snow cover was at least 60 cm thick. The possibility then exists that transformer stations in southern Ontario could experience more frost penetration than those in northern regions.

4.0 RECOMMENDATIONS

Because of the inconclusive results obtained from the test sites during the last two winters, continued monitoring of the frost heave instrumentation should be discontinued for the present. The reasons behind this result are i) the above normal winter temperatures experienced at most of the test sites during both years, ii) damaged instrumentation and test footings and iii) sparse and sometimes questionable data.

An evaluation of frost heave characteristics of small diameter footings should ideally be done under controlled, and therefore known, temperature and soil conditions. This type of testing could be achieved by constructing large scale, instrumented models within a temperature-controlled environment. In this manner, test conditions could be modified as required and monitoring could continue throughout the year. The Civil Research Department will soon have such a testing facility which could then be made available for studying the behaviour of various types of footings under freezing conditions.

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TABLE I

Port Hope TS (1987-1988)

Elevation change of footings (cm) relative to Oct 6/87 readings

Footing #	Oct 6/87	Jan 21/88	Feb 18/88	March 14/88	April 8/88
1	-	-0.2	-0.1	0	-0.2
2	-	-	-	-	-
3	-	-0.2	0.1	0.1	0
4	-	-0.2	0	0.1	0.9

Movement of Frost Heave Gauges (cm) relative to Oct 6/87 readings

Gauge #					
A	-	-	-	-	-
B	-	(0.3)	(0.3)	(1.0)	(-0.3)
C	-	(1.0)	(1.6)	(0.3)	(-2.2)
D	-	(0.8)	(0.5)	(0.2)	

Frost Depth Gauges (cm)

Gauge #					
A	-	-	-	-	-
B	-	-	45.7	48.3	-
C	-	-	47.0	42.5	-
D	-	-	53.6	56	-

Thermocouple Readings (^{o}C)

No					
1	10.1	1.2	0	3.7	5.8
2	12.4	2.3	2.3	4.8	4.9
3	13.2	2.9	3.3	4.9	4.3
4	13.9	3.9	3.2	5.6	3.5
12	8.4	0.7	0.6	3.2	5.4

No 1 = 30.5 cm below ground level
2 = 61 cm below ground level
3 = 91.5 cm below ground level
4 = 122 cm below ground level
12 = 122 cm away from footing but located just under insulation

TABLE II

Ottawa-Hawthorne TS (1987-1988)

Elevation Change of Footings (cm) relative to Dec 23/87 readings

Footing #	Dec 23/87	Jan 6/88	Jan 22/88	Feb 11/88	March 14/88	April 5/88
1	-	-0.2	0	0.3	0.3	0.2
2	-	0	0.5	0.3	0.3	0.5
3	-	0	0.3	0.6	0.4	0.1
4	-	0.1	0.4	0.6	0.4	0.2
1A	-	0	0.3	0.5	0.5	0.7

Movement of Frost HeaveGauges (cm) relative to Dec 23/87 readings

Gauge #						
D	-	0.6	0.5	1.9	1.9	0.6

NOTE: no movements recorded at Gauges #A, B and C, between test footings

Frost Depth Gauges (cm)

Gauge #						
A	-	-	0	15.2	15.2	0
B	-	0	0	12.7	12.0	0

NOTE: Gauge #C broken on Jan 22/88

TABLE III

Pinard TS (1987-1988)

Elevation Change of Footings (cm) relative to Nov 3/87 readings

Footing #	Nov 3/87	Dec 22/87	Jan 8/88	Feb 11/88	Feb 23/88	March 6/88
1	-	0.3	0.3	0.3	0	0.8
2	-	-0.8	-0.8	-0.8	0	0
3	-	1.0	1.0	1.0	-0.3	1.5
4	-	-2.0	-2.0	-2.0	0.3	0

Movement of Frost Heave Gauges (cm) relative to Sept 22/87 readings

Gauge #						
A	-	0	0	0	0	0.6
B	-	0	0	0	0	0
C	-	0.6	2.5	2.5	0.6	4.4

Frost Depth Gauges (cm)

Gauge #						
B	0.3	7.6	8.3	8.3	7.6	7.6
C	8.9	6.4	7.0	7.0	6.4	6.4
D	9.5	5.7	5.4	5.4	5.7	5.7

Thermocouple Readings (^{o}C)

No						
1 (183 cm BGL)					4.8	3.8
2 (122 cm BGL)					3.3	2.6
3 (61 cm BGL)					1.3	1.7
4 (0 cm BGL)					-7.3	2.8
5 (30 cm AGL)					-13.7	1.0

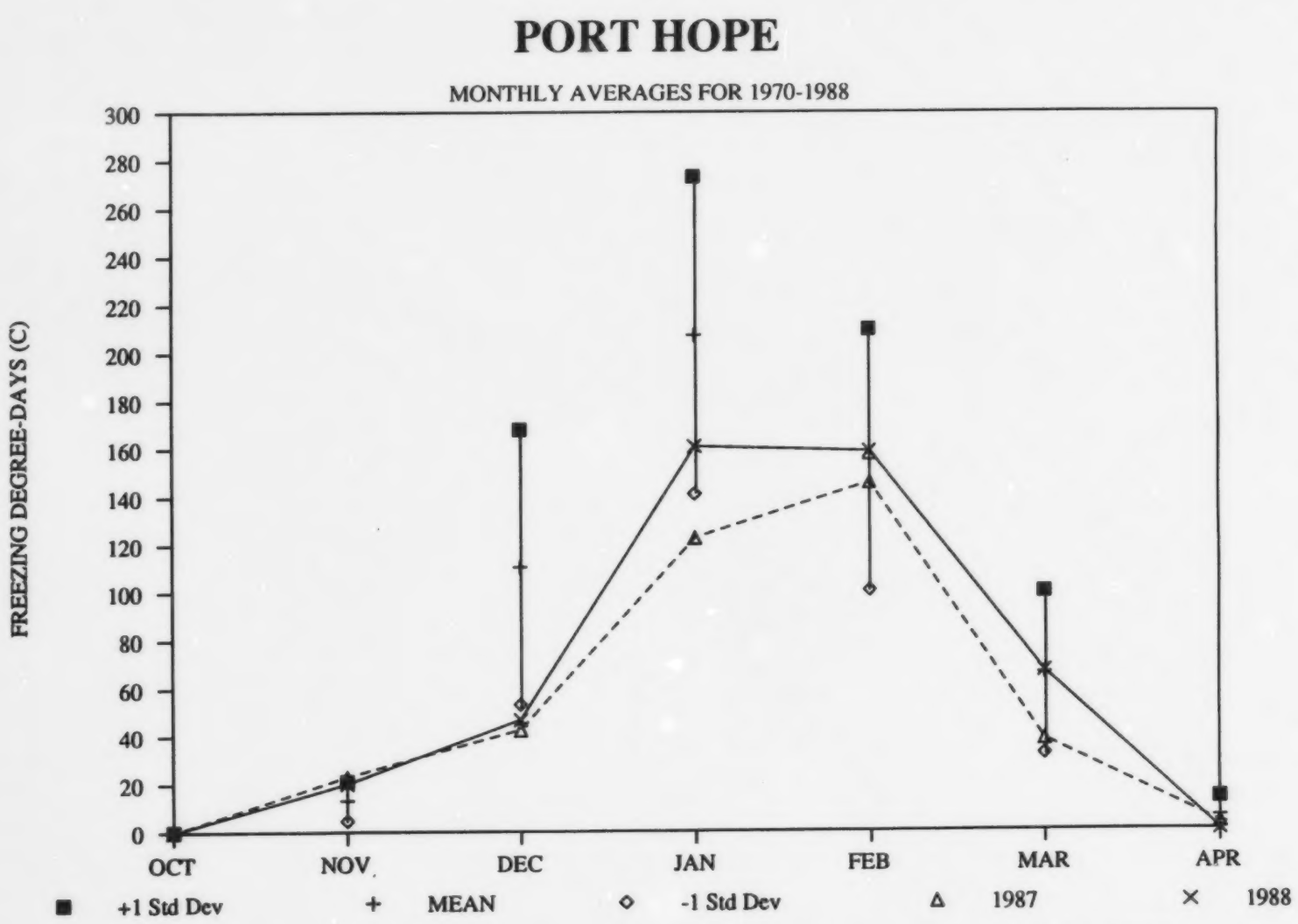

Figure 1: Monthly Freezing Degree-Day Averages - Port Hope 1970-1988

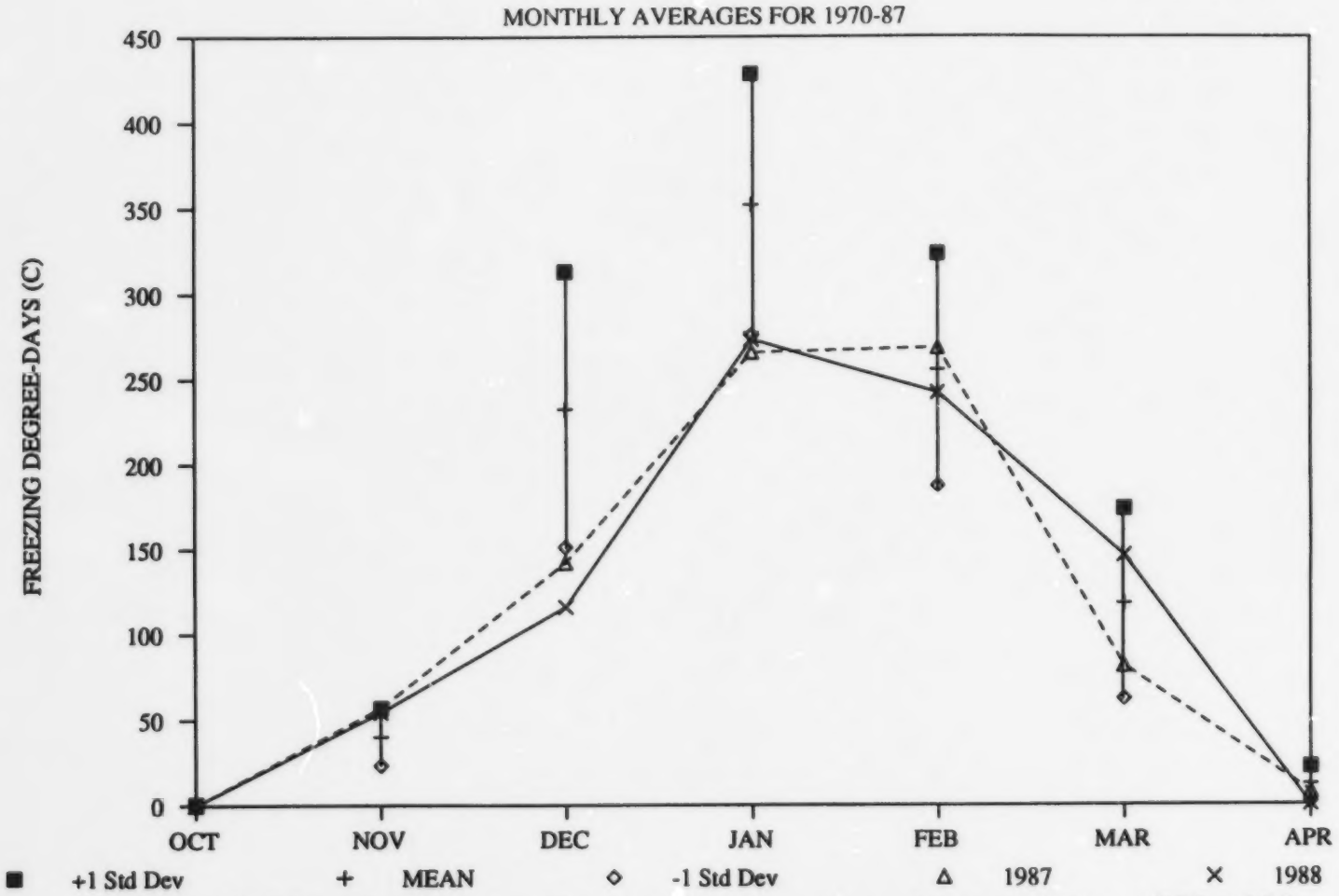

Figure 2: Monthly Freezing Degree-Day Averages - Ottawa CDA 1970-1988

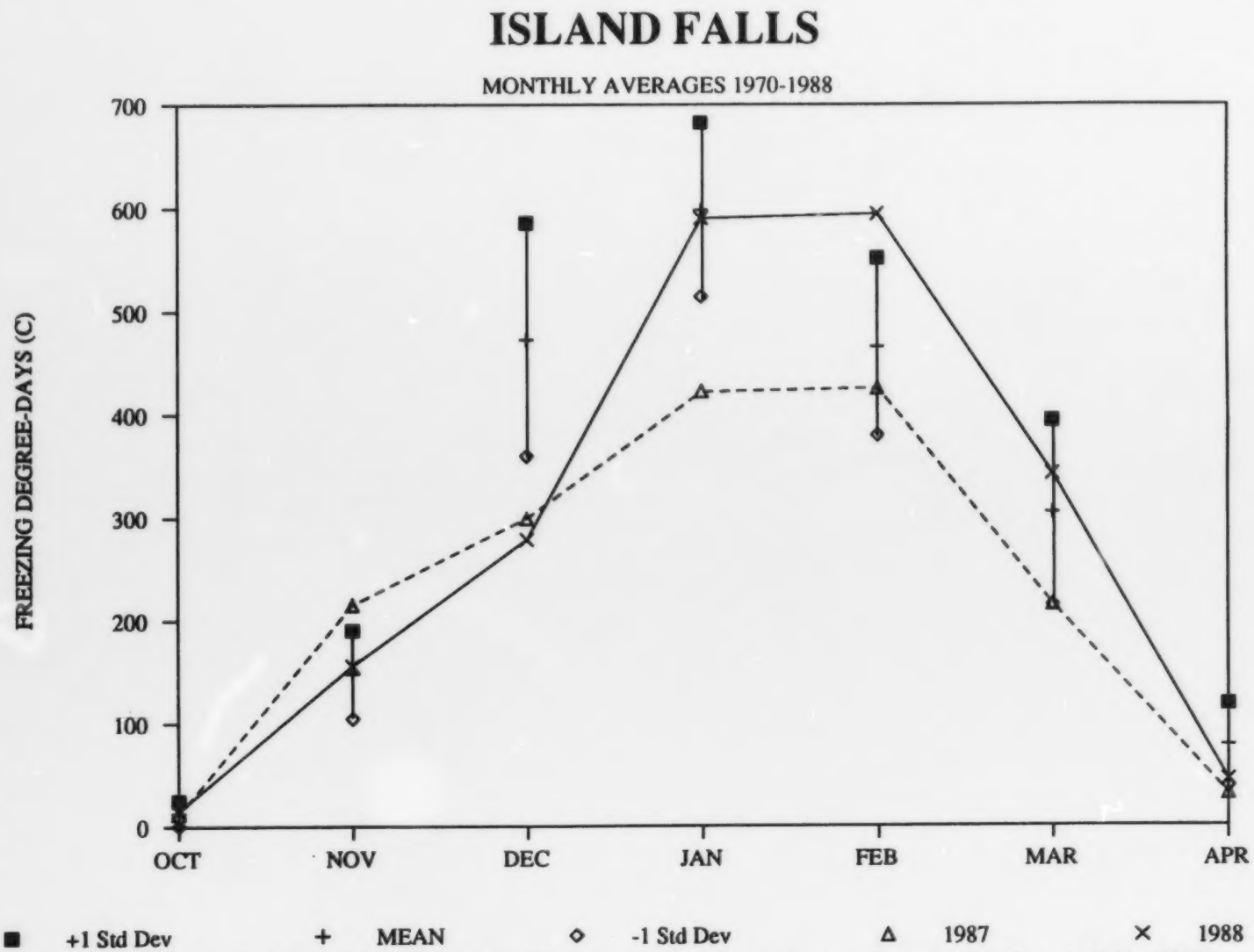

Figure 3: Monthly Freezing Degree-Day Averages - Island Falls 1970-1988

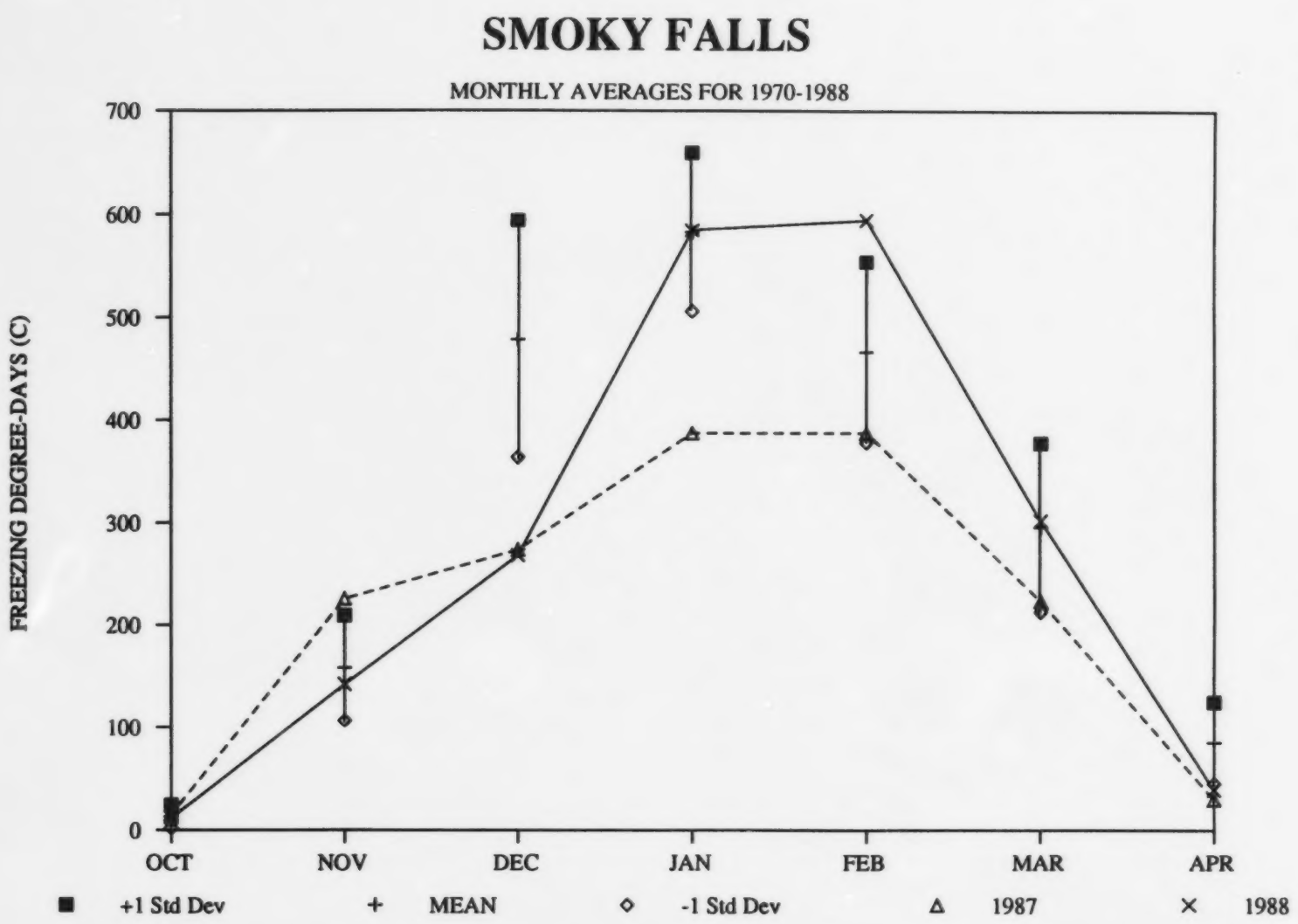

Figure 4: Monthly Freezing Degree-Day Averages - Smoky Falls 1970-1988

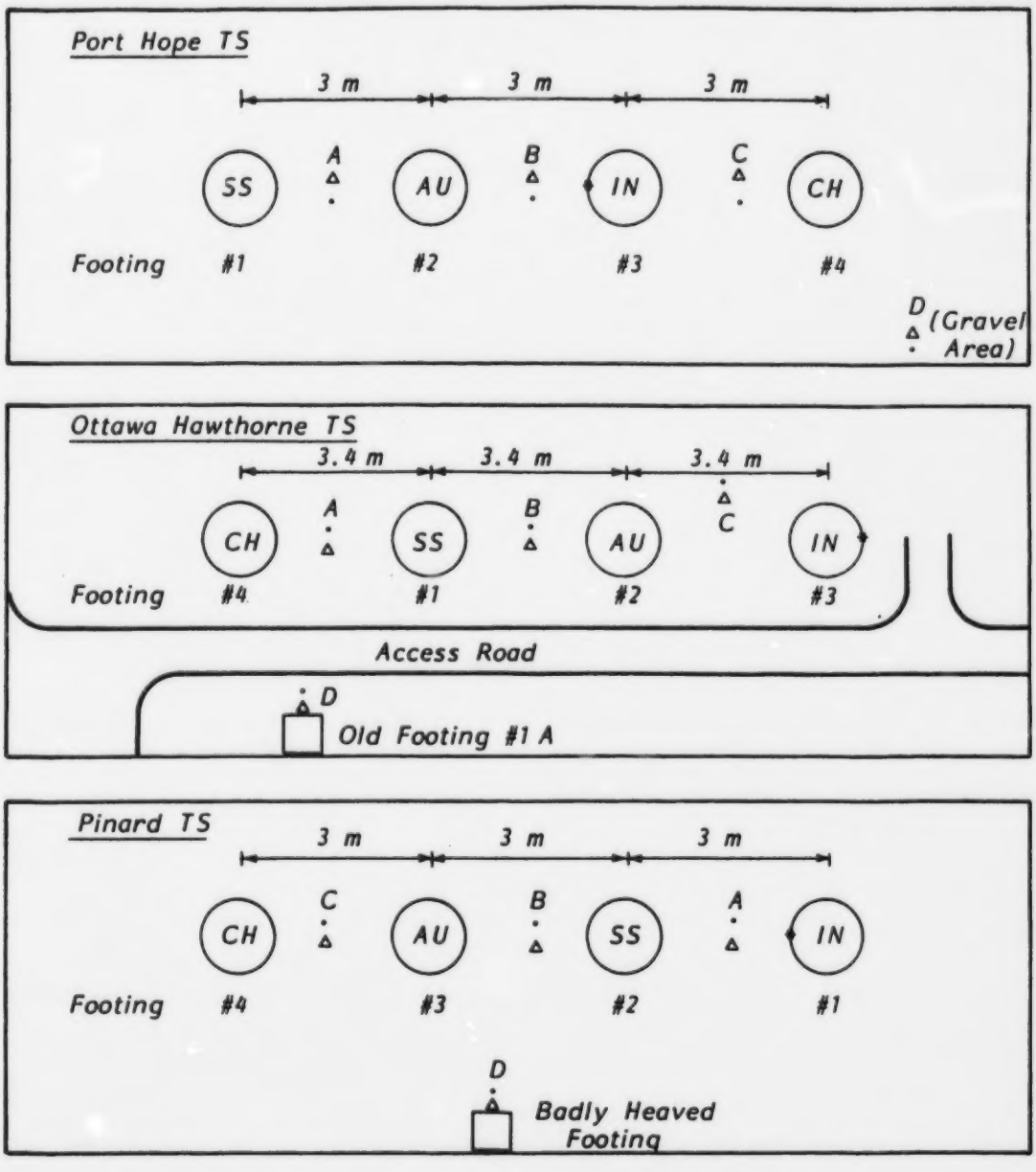

Figure 5: Frost instrumentation and test footings layout at three test sites

PINARD T.S.

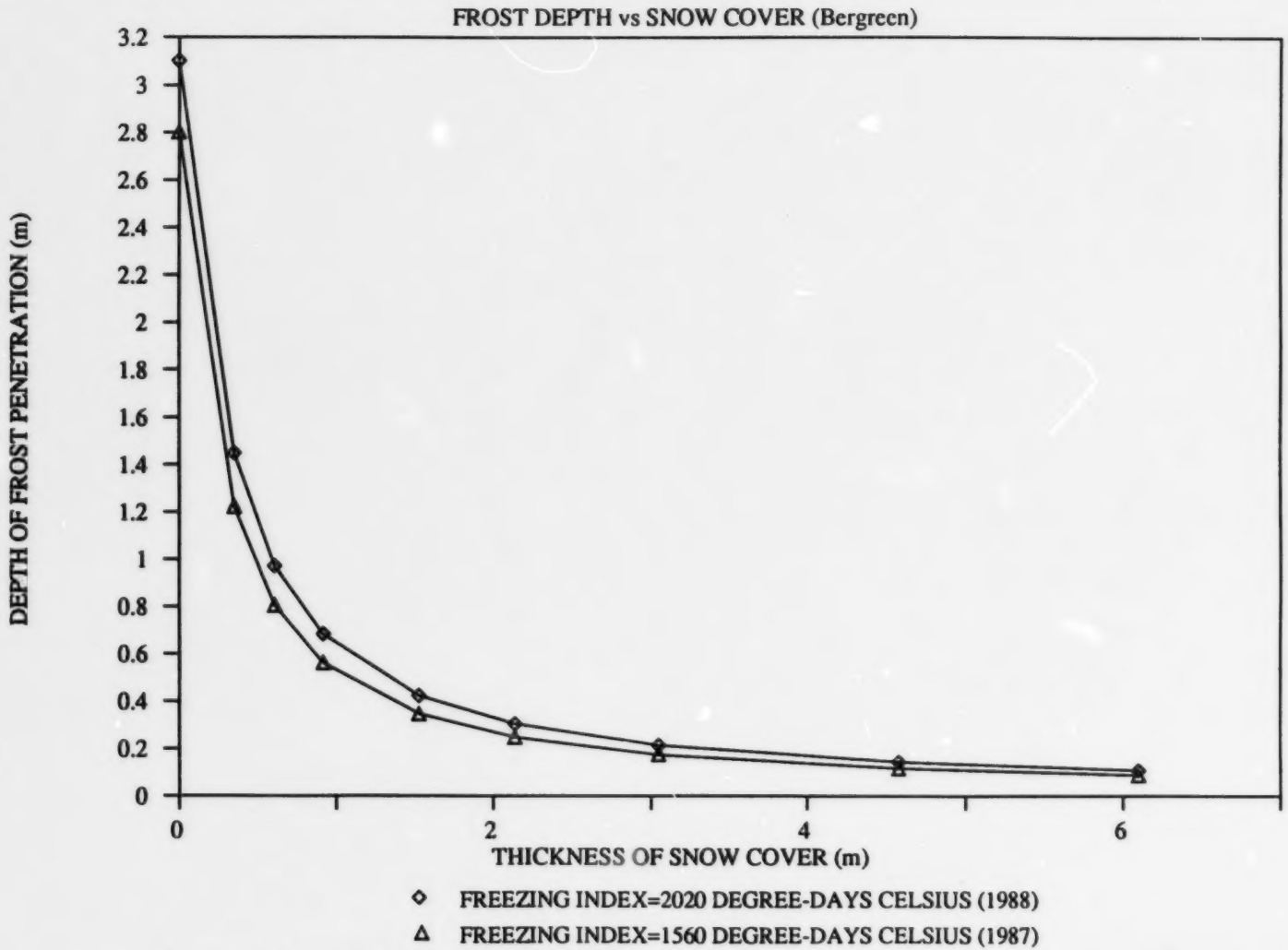

Figure 6: Theoretical frost depth versus snow cover at Pinard TS